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Pavement Primary Response using Influence Function and Peak Influence Function

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Abstract. It was identified in previous research that errors in theoretical damage much associated with the influence function calculation. Thus, this paper present the efficient prediction of primary response due to dynamic vehicle loading using influence function and peak influence function approach. In order to provide the realistic loading condition, dynamic road response model with idealised loads representative by mathematical quarter-truck model with two degree of freedom was excited by a random road surface profile which equally spaced points along the simulated road with various different speeds. Consequently, the simplified computational approach (peak influence function method) was identified only a few points gave a small different compare with the influence function method for along the longitudinal distance. In order to identify the impact of both methods, further implementation was done to calculate fatigue damage (horizontal tensile strain at the bottom of a bound layer) or rutting damage (vertical compressive strain at the top of the subgrade layer) predicted by constant load moving at varies speed. It was found that the differences in response are particularly small and increased steadily as the increasing of the vehicle speed. It was conclude that the simplify calculation was able to predict stresses and strains sufficiently accurately and identified relatively small errors into the pavement damage prediction. Hence the simplification in particular much reduced the computation time sufficiently and minimized the computer resources significantly.

Introduction

Result from previous research showed that dynamic wheel loads (DWLs) are an important factor in pavement failure and fatigue damage [1-3]. Thus, it is important to consider dynamic effects in pavement design because dynamic pavement responses, such as displacements, strains and stresses can be significantly different from their static counterparts [3-5]. Previous research has also shown that peak forces applied by a fleet of heavy goods vehicles are not distributed randomly along the road but are applied to similar locations [6], [1], [8]. This has been termed spatial repeatability and means that road failure will be governed by localised peaks in the damage profile rather than the mean level damage [8]. Hardy and Cebon studied the importance of the dynamic response of flexible pavement structure on primary responses due to dynamic, moving wheel loads [9]. They concluded that the response of the road was sensitive to vehicle speed but that the effects of loading frequency were small. Consequently, in most situations a quasi-static model of the road structure was considered adequate.

Loading Conditions

In order to consider a realistic loading condition, a simple quarter-truck vehicle simulation with two degrees of freedom (as shown in Fig.1 and Table 1) was excited by a random road surface profile which is described by the elevation of equally spaced points along the road. The quarter-truck model has been used by many previous researches [1], [5], [9-10]. This simple model captures many of more important characteristics of dynamic tyre forces even though it does not contain detailed suspension nonlinearities and complexities of sprung mass motion that are typical of heavy vehicles [2]. State-space equations were generated for the quarter-truck model which solved in the time domain. Fig. 2 shows the input surface profile corresponding to a road with an IRI of 2 and Fig. 3 shows an example of the resulting DWL for a vehicle speed of 20m/s. The initial pavement surface profile were generated by applying a set of random phase angles uniformly distributed between 0 to 2π, to a series of coefficients derived from the desired roughness spectral densities (see [1] for further details).

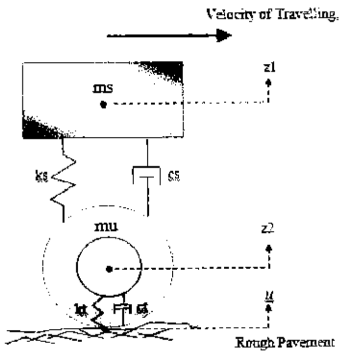


Fig. 1. Quarter truck vehicle model

Table 1: Quarter –truck model parameters

Parameters	Symbols	Values
Sprung mass	mu	8900 kg
Unsprung mass	ms	1100 kg
Suspension spring	ks	2MN/m
Suspension damper	kt	40kNs/m
Tire spring	cs	2 MN/m
Tire damper	ct	4kNs/m

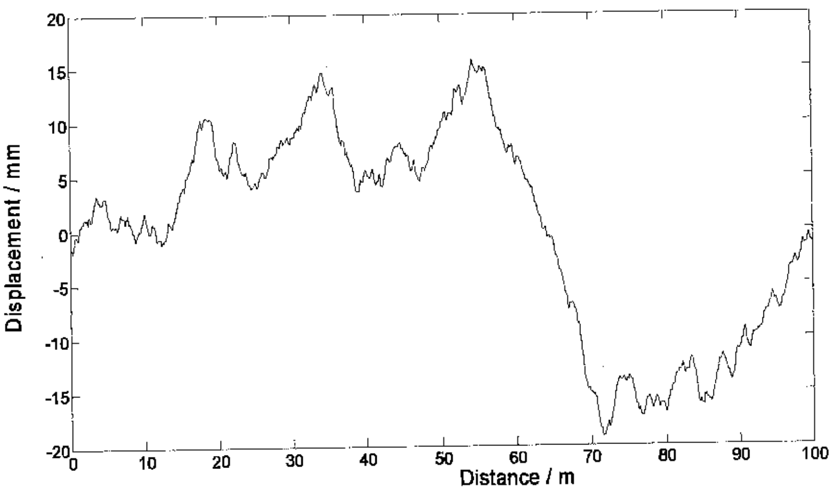


Fig. 2: Initial surface profile

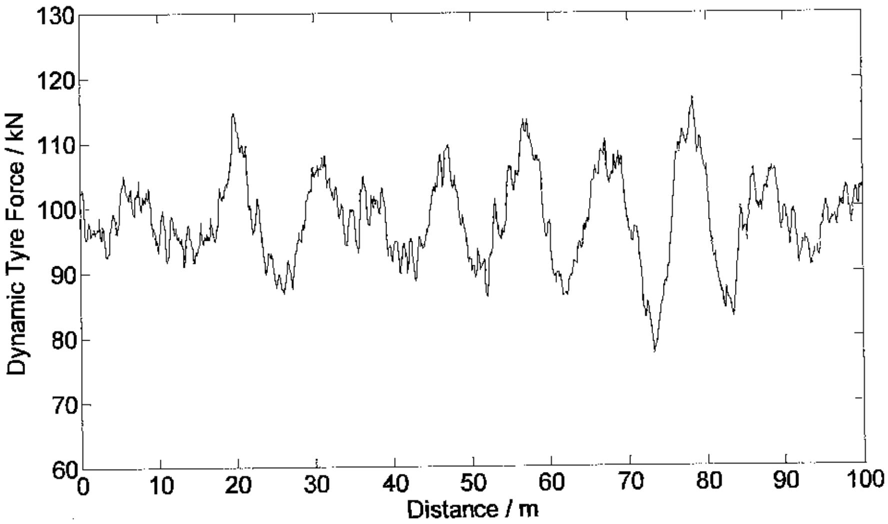


Fig. 3: Dynamic wheel load at 20m/s.

Pavement Structure

A typical flexible pavement structure was modelled as a three layer system with the load uniformly applied on the surface over a circular contact area 0.3m in diameter. The layer configuration in this study comprised a 0.2m asphaltic layer over a 0.2m a granular subbase layer over the natural soil (subgrade) which is assumed infinite in vertical extent.

All layers are assumed to be infinite in horizontal extent, homogeneous, linear elastic and isotropic. Poisson's ratio was taken to be 0.35 for the asphaltic layer and 0.4 for the unbound layers. The stiffness modulus of the asphaltic layer was taken to be 6.9GPa, 7.9GPa and 8.7GPa for vehicle speeds of 10m/s, 20m/s and 30 m/s respectively. The stiffness modulus of the subbase and subgrade were taken to be 100MPa and 40MPa respectively.

Importance of Speed in Primary Response Determination

Determining primary response involves simulating the DWLs generated by a vehicle travelling over a specified road profile. Two different methods for calculating the primary response has been studied; the influence function method and the peak influence function method at three vehicle speeds (10, 20 and 30m/s).

The effect of vehicle speed on pavement response has been the focus of several studies and several authors have concluded that when the wheel passes more quickly over a specific location on the road the time available for plastic (permanent) deformation to occur is reduced and there will be reduced road damage [6]. However, Cebon performed a theoretical study in which he showed that under some conditions, DWLs can increase with vehicle speed and thus increase theoretical road damage [2]. Gyenes noted that the increase in DWLs with speed is compensated for by the shorter duration of the load and there is little additional increase in the average rut depth along a road arising from dynamic truck behaviour [6].

Pavement Primary Response

Current analytical (or semi-analytical) pavement design procedures relate fatigue damage and rutting to the horizontal tensile strain at the bottom of a bound layers and the vertical compressive strain at the top of the subgrade layer respectively which are typically calculated using a layered elastic model. Alternatively, Odemark's Method of Equivalent Thicknesses (MET) can be used to transform a layered system into a half-space and Bousinesq's equations can be used to calculate stresses, strains and displacements [11-12].

The resulting vertical and horizontal components of stress and strain calculated using MET due to a uniformly loaded circular area are shown in Figure 4. It can be seen from this figure that, as expected, the radial strain is tensile at the bottom of the bituminous layer and the vertical strain is compressive at the top of the subgrade.

Influence Function Method

The pavement primary responses shown in Fig. 4 have been calculated due to a particular applied load. Since the load will vary along the road due vehicle dynamics these primary responses have been normalised by the applied load and are termed influence functions. The influence functions are then combined with the DWLs to give the response y at a particular location x as a function of time t using the following equation (see Fig. 5):

$$y(x,t)=F(t) \cdot I(V, x\text{-}Vt) \tag{1}$$

Where $I(V,x-Vt)$ is the influence function for speed V and distance $x-Vt$ from the point of application of the load. Figure Fig. 6(a) and 6(b) show the results of this calculation for a single point on the road surface in terms of strain at the base of the asphalt layers (Figure 6(a)) and strain at the top of the subgrade (Fig. 6(b)).

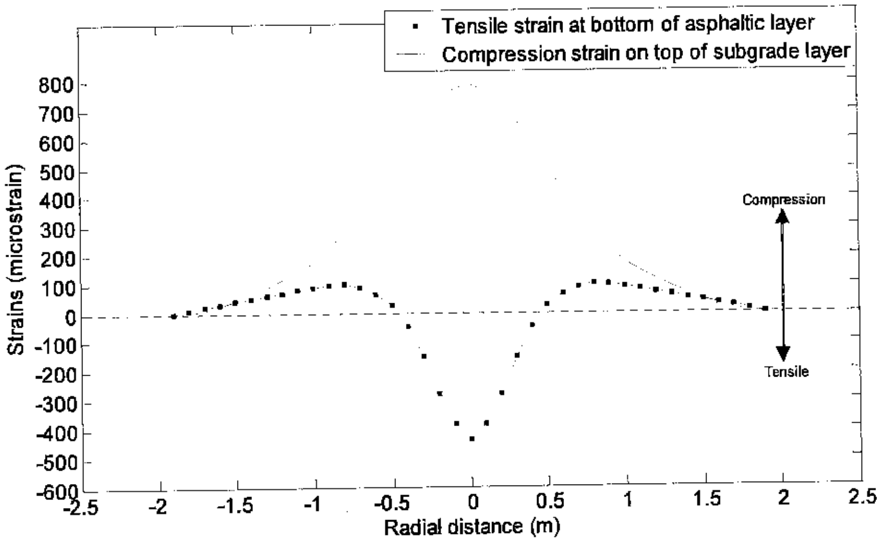
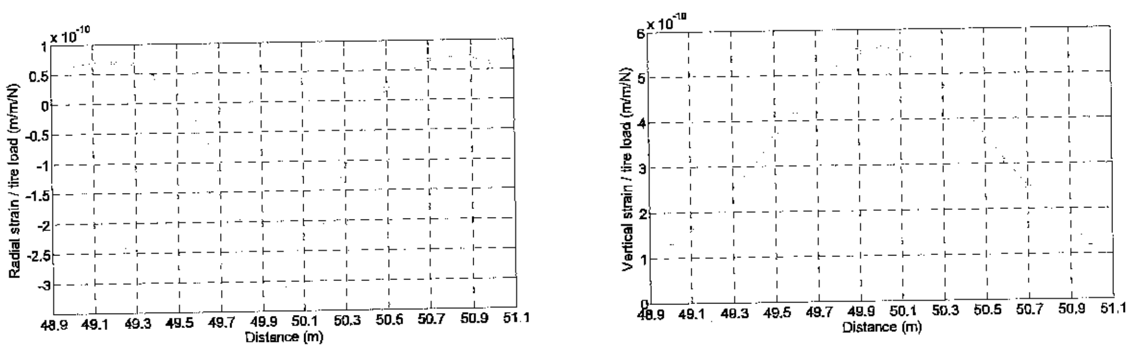


Figure 4: Critical strains



(a) (b)

Fig. 6: Influence function under the load

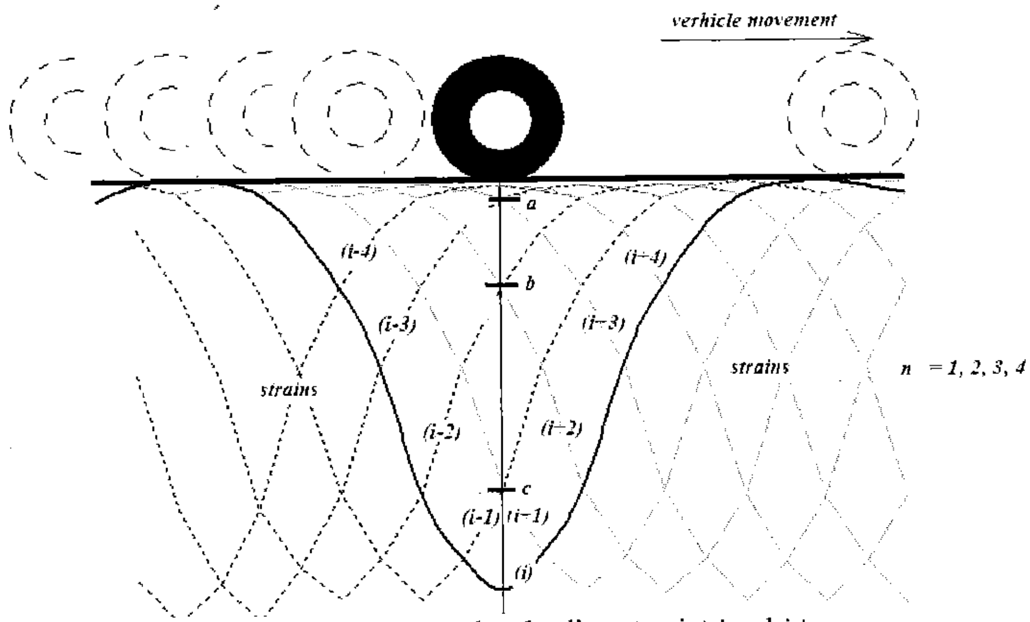


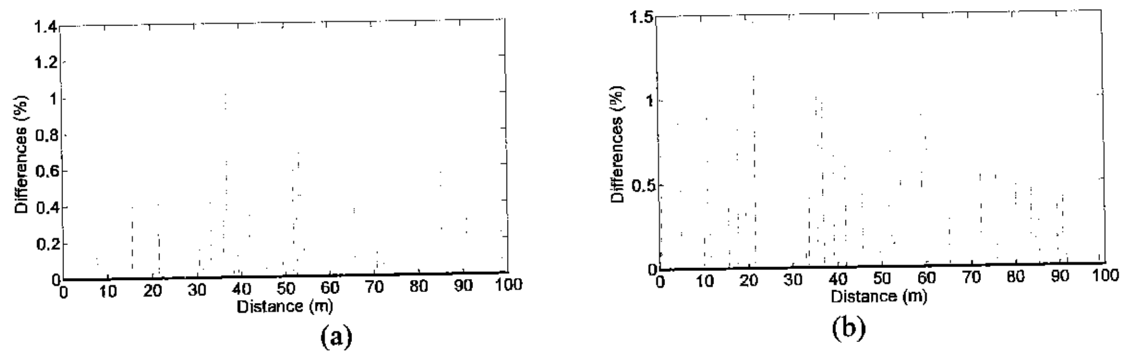
Fig. 5: Primary response when loading at point i and $i \pm$n

Peak Influence Function Method

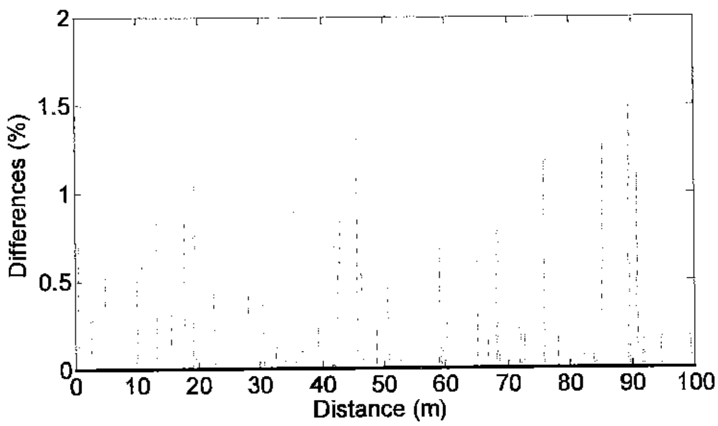
A further simplification can be made to the influence function method is the peak response occurs directly over the point of interest. In this case, Equation [1] reduces to:

$$y(x)=F(x) \cdot I(V, x) \quad (2)$$

To examine the effects of this simplification, results from simulations undertaken using Equations [1] and [2] have been compared using vehicle speeds of 10m/s, 20m/s and 30m/s. Fig. 7(a) shows the percentage difference in compressive strain on top of the subgrade between the two methods at 20m/s for each point along the road and Fig. 7(b) for 30m/s. It can be seen that for the 100m of road length simulated, the maximum difference are small with approximately 1% for a vehicle speed of 10m/s, 1.5% for a vehicle speed of 20m/s and 1.7% for vehicle speed 30m/s.



(a) (b)



(c)

Fig. 7: Differences compressive strains using influence function method and peak influence function method using vehicle speed at 10m/s, 20m/s and 30m/s respectively.

Fatigue and Rutting Damage

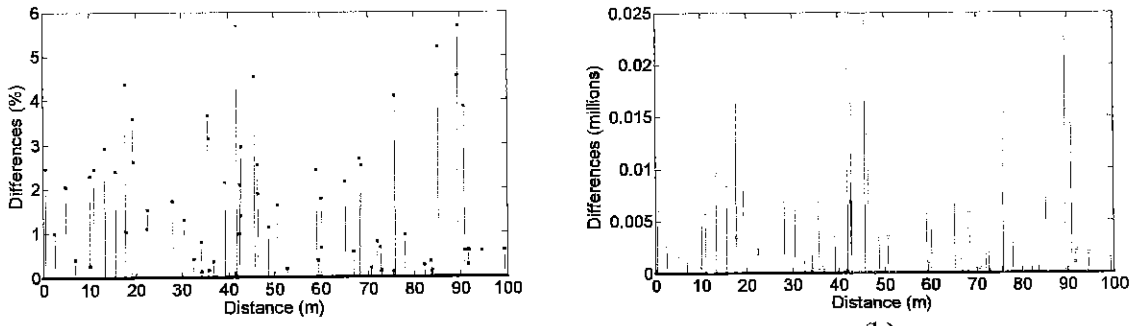
Fatigue cracking and rutting are the two principle type of distress considered in this study. In fatigue cracking failure criterion, the allowable number of load repetitions (*Nf*) that caused fatigue cracking is related to the tensile strain (ε_t) at the bottom of the asphaltic layer as:

$$N_f = k_1(\varepsilon_t)^{k2} \tag{3}$$

The major factors that affect the constants k_1 and k_2 are the volumetric proportion of binder V_B and its initial Softening Point SP_i. The fatigue constants k_1 and k_2 for typical were determined from the equation given in Brown and Brunton (1992). For rutting damage, the allowable number of load repetitions is related with the vertical compression strain on top of the subgrade using:

$$N_r = k_4(\varepsilon_c)^{-k_3} \tag{4}$$

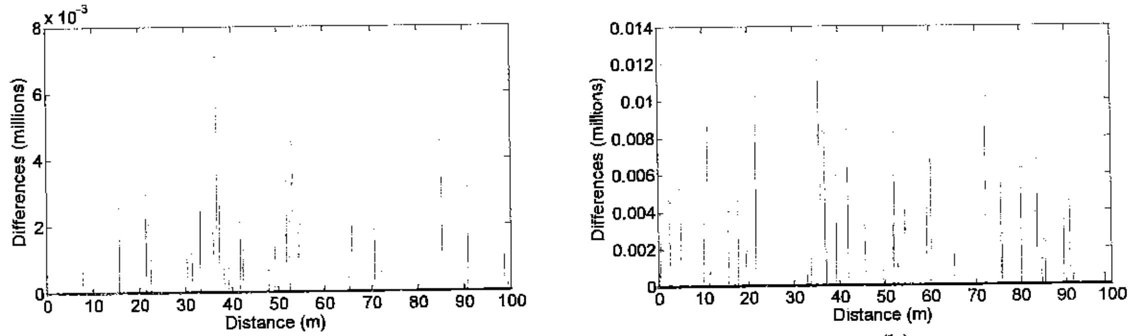
Where, k_3 and k_4 are constants which can be calibrated to match the field observations. Fig. 8(a) shows the difference in rutting between the two methods for a vehicle speed of 30m/s. It can be seen from this figure that the maximum difference is approximately 5.7% which is greater than the difference in subgrade strain because of the exponent used in Equation (4). The actual maximum difference in predicted life is approximately 0.025 million cycles (Fig. 8 (b)). There were no differences found between the two methods for fatigue damage. This is probably due to the fact that the fatigue influence function is narrower than the rutting influence function which means that changes in dynamic load over are likely to have more effect.



(a) (b)

Fig. 8: Differences in percentage and in predicting life for 20 m/s

Fig. 9(a) and 9(b) show similar results for a simulation speed of 10m/s and 20m/s. It can be seen from Fig. 9(a) and 9(b) that the differences in predicted life between the two methods has increased from approximately 0.007 million cycles 0012 million cycles. This shows that the difference between the two methods is significantly affected by the speed of the vehicle with higher vehicle speeds increased the magnitude of the difference.



(a) (b)

Fig. 9: Difference in predicting life for 10m/s and 20 m/s

Fig.10 shows the permanent deformation profile calculated by using both approach at distance 41 to 47 m. In this figure it shown the potential different appears among the point situated at the higher slope where the permanent damage calculated among the nearest point is considerable different compare with others points.

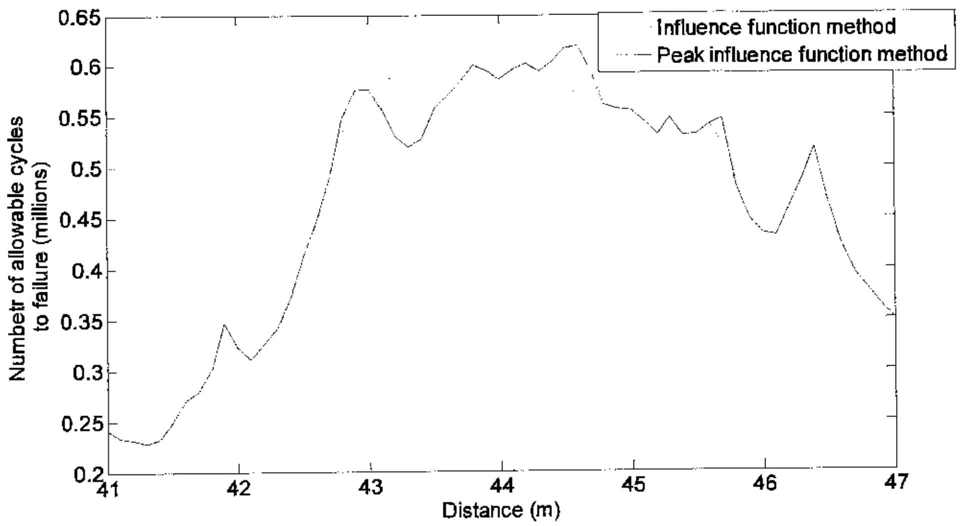


Fig. 10: Number of allowable load to permanent deformation profile calculated using Two different methods

Considering the reality of traffic loading condition will contain a distribution of axles load between unladen and fully laden, the study was further to take into account realistic axle load variation. To achieve this adjustment, the sprung mass (see Table 1) was divided into two other weight bands of 1/3 and 2/3 of fully laden. As a result loading of 1/3 of fully laden were shown an increasing of the difference between both method and in number of point contributed (Fig. 11(a) and Table 2). It shows that there has a considerable increasing in maximum differences for vehicle loading 1/3 and 2/3 of fully laden when truck moving at 10m/s, 20m/s and 30 m/s.

In addition, considering the effect of material properties, there were two bituminous properties effect on the percentage differences between the two methods were investigated. Fig. 11(a) shows maximum differences in rutting for pavement surface layer using bitumen grade 50 with bitumen content 10.4%, 11.7% and 13.1% when truck moving at 10m/s, 20m/s and 30m/s. It can be seen from the figure that the maximum differences is higher for lower bitumen content at the same truck speed and higher for higher truck speed. The same pattern shows in Fig. 11(c), the higher pavement surface temperature result the lower maximum differences. The reason for this is due to the fact that higher compression strain result from higher temperature is narrower than compression strain at lower temperature for the same truck speed at 20m/s (Fig. 12(a)). It can also be seen from Fig. 12(b), the higher the truck speed, the compression strain are getting lower, although for the entire length of the road some nodes will result higher compression strain (narrower) as the truck speed become higher due to dynamic loading. Although, in fact increasing considerable different among the nearest point for higher truck speed likely to give more effect. As a result more points along the pavement are different using both methods (see Table 2). Consequently, in all cases the higher truck speed, the maximum differences are become higher.

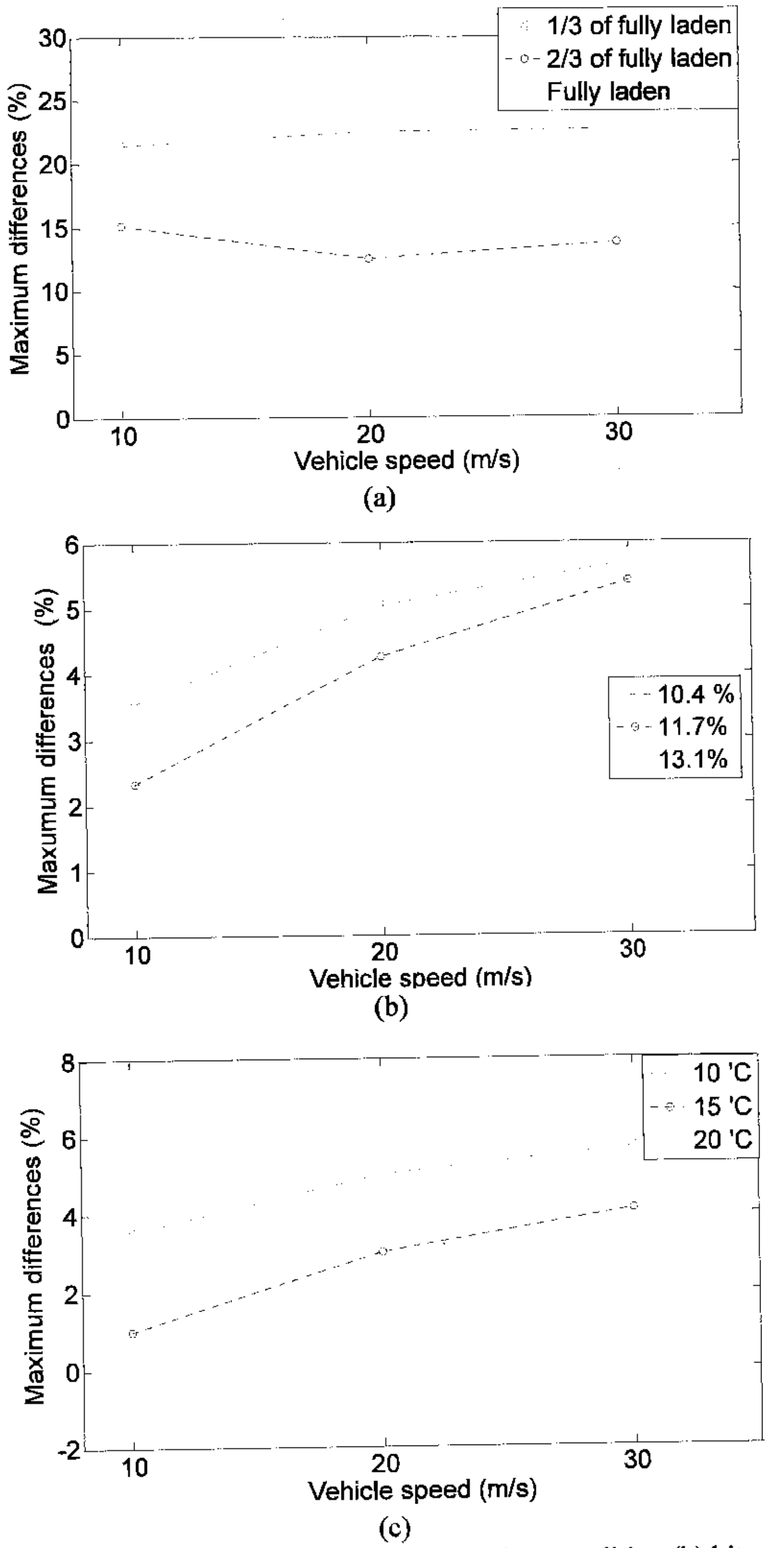
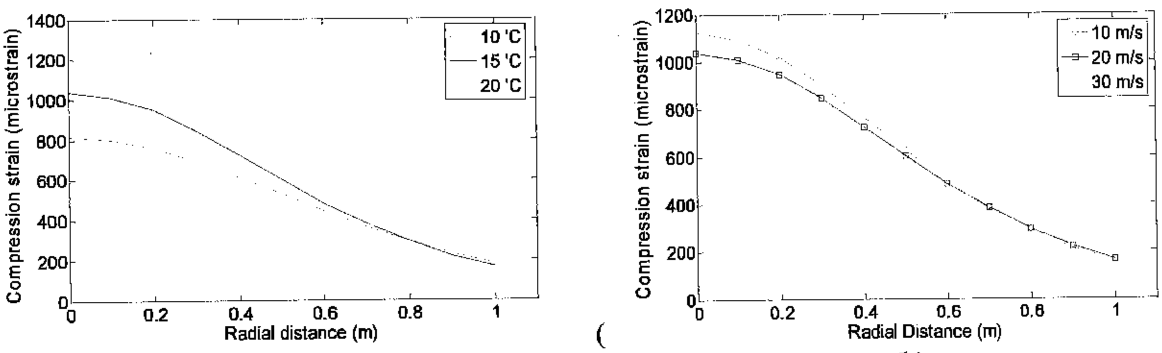


Fig. 11: Maximum difference of rutting for varying; (a) loading condition,(b) bitumen content, (c) node spacing and (d) surface layer temperature at varying vehicle speed



a) (b)

Fig. 12: Compression strain for varying condition; (a) different temperatures, (b) different truck speeds

Table 2: Number of nodes shows in differences

Variables		Permanent deformation failure, N_r		
		Vehicle speed (m/s)		
		10	20	30
1.	Truck loading Condition			
	1/3 of fully laden	218	339	412
	2/3 of fully laden	168	182	202
	Fully laden	46	54	57
2.	Bitumen content			
	10.4 %	36	49	65
	11.7 %	13	35	53
	13.1 %	2	22	31
3.	Surface layer temperature			
	10℃	36	49	65
	15℃	2	21	29
	20℃	0	0	3

Conclusions

(i) Narrower compressive strains will reduce the maximum difference of rutting calculated using influence function and peak influence function and hence the number of nodes in contribution.

(ii) Lower truck load, higher surface temperature and lower bitumen content in bituminous layer increase the differences in compression strain on top of the subgrade layer by using influence function and peak influence function method.

(iii) Increasing in compression strain differences result in increasing the differences in permanent deformation.

(iv) No difference resulted in tensile strain at the bottom of the asphaltic layer calculated using both method for low vehicle speed and each loading condition and hence the fatigue damage.

(v) The differences between the two methods were increased as the truck moving for higher speed for all cases.

(vi) The accuracy in predicting pavement damage using peak influence function method is appropriate due to low differences in all cases.

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